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A STRONG TENDENCY OF RESEARCH AND APPLICATION DEVELOPMENT ON SEISMIC CONTROL FOR STRUCTURES IN CHINA

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ABSTRACT

This paper describes the most recent state of a strong tendency of researches and application development on seismic control for structures in P R China, also introduces the present researching results completed by authors in these fields, including seismic isolation, energy dissipation, other passive control systems, active control systems and hybrid control systems for structures. A very bright future of seismic control for structures in China is also discussed by authors in this paper.

KEYWORDS

Seismic control; seismic isolation; energy dissipation; passive control; active control; hybrid control.

INTRODUCTION

During earthquake attacks, the building structure which is fixed on the ground will respond gradually increasing from the building bottom (ground) to the building top, liking an "Amplifier" (Fig.1.a). This will result in damage or collapse of structure or results in damage of nonstructural components, decoration and equipment's facilities in building due to the large response of structure. In order to reduce the response and avoid the damage of structure, some controlling methods have been developed :

Rigid Structure System

Increasing the structural stiffness to be very more, form a "Rigid Structure System"(Fig.1.b) whose structural response may be nearly as same as the ground motion. But this kind of structure system is very expensive and very difficult to realize in some cases.

Flexible Structure System

Decreasing the structural stiffness to be very small, form a " Flexible Structure System " (Fig.1.c) whose structural response should be also very small. But this kind of structure system is not suitable for normal use because it is too flexible under wind load or minor earthquakes.

Soft First Story Structure System

Making the first story columns very soft and allowing it to deform into the inelastic range to dissipate the energy thus reducing the response of the upper structure, form a "Soft First Story Structure System" (Fig.1.d). This system can reduce the upper structure response very effectively, but the building may collapse in severe earthquake because of the large inelastic deformation of first story columns.

Inelastic Structure System

Increasing the structural ductility and allowing the structural elements or joints to work in inelastic range to dissipate the energy of structure under earthquakes, thereby reducing the structural response, by forming an "Inelastic Structure System" (Fig.1.e). This is the general structural system for earthquake resistance in many countries including China at present. But its usefulness is limited or it is not very safe in some cases. First, it is difficult to control the structural damage level due to the inelastic deformation, and it may be quite dangerous in severe earthquake unpredicted before. Secondly, it is not able to be used in some important structures whose elements are not allowed to work in inelastic range, such as some buildings whose decoration is very expensive, nuclear power plant, museum building, and so on. Thirdly, it is not possible to be used for buildings with precise instruments in it.

The Base Isolation System (Fig.1.f)can reduce the structure response very effectively by keeping the advantages of " Soft First Story Structure System ", but it changes from the soft first story columns into an isolation sliding layer only.

The Energy Dissipation System (Fig.1.g) can also reduce the structural response by keeping the advantages of "Inelastic Structure system", but it changes from allowing the structural elements or joints to work in the inelastic range become to allow only nonstructural components to work in inelastic range for dissipating energy and protecting the structure from damage in earthquake.

The Structural Controlling System (Fig.1.h,i.) keeps the advantages of "Rigid Structure System" and "Flexible Structure System" by changing the dynamic characteristics(Mass, stiffness or damping) of the structure.

China is very frequently attacked by severe earthquakes every year and may be attacked by several very strong earthquakes in coming years depending seismic prediction. To find a more safe and suitable way for earthquake resistant structure system of buildings is a very urgent object. The structural control systems provides a very advanced way for this object.

Because the traditional method and system are not satisfied in many cases for earthquake resistance, so it is limited to be developed in future although it is used very common at present. China has paid more attention to find out some new systems for earthquake resistant structure: Base Isolation, Energy Dissipation and Structural Controlling System. Some available results of research have been obtained , and the some systems has been used successfully in engineering application in China (Zhou, 1989, 1990a)

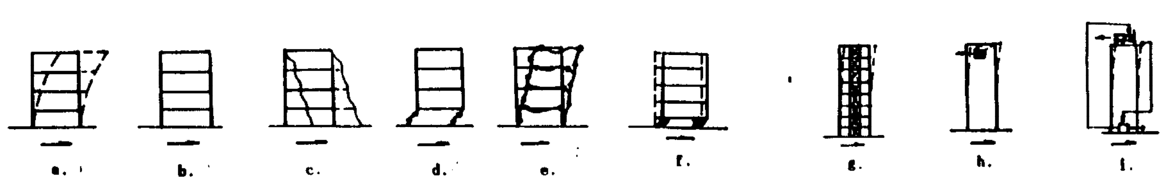


Fig.1 Development of earthquake resistant structural system

BASE ISOLATION SYSTEM

The history of application on seismic isolation in China has proved that the isolation system is more safe, economic and simple than the traditional structure system, specially suitable for using in the cases where the earthquakes are unpredictable. In mainland China, About 40 existed ancient buildings, towers and temples built thousands years ago with isolation concept have successfully withstood several strong earthquakes. In recent 20 years, there are 15 buildings and 21 bridges being built with base isolation, which isolators were rubber bearings, sand sliding layer or graphite layer.

In order to solve some problems for more wide application of isolation in China, two 8-stories R.C.frame dwelling buildings are to be built for full scale tests. Both structures of buildings are the same, but one was base isolated with reinforced rubber pads, another was base fixed. To cooperate the tests of these two buildings, a great numbers of low cycle fatigue tests for isolators and shaking table tests for building models were carried. Based on the applications, testing results and analysis, a set of optimal design methods, computer programs were raised in China.

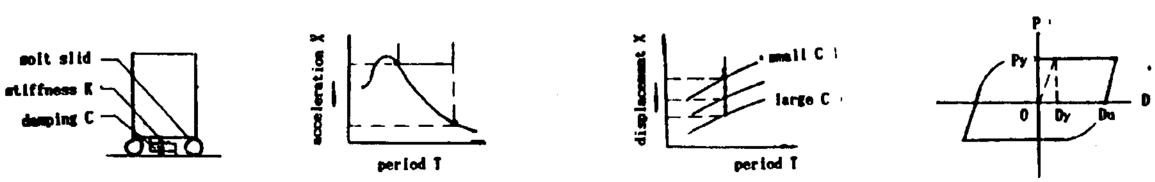
Design and Application of Base Isolation System. in China

In general case, the base isolation device combining with energy dissipation device requires to possess three basic characters (Fig.2.a):

Soft sliding. The structure can softly slide on the base in severe earthquake. This character can isolate the horizontal vibration from ground motion to structure, make the natural period of structure very long, then reduce the acceleration response of structure effectively (Fig.2.b).

Certain amount of damping C. It will dissipate the energy input to the structure then attenuate the displacement response of structure in earthquake (Fig.2.c).

Suitable horizontal stiffness K. It will provide the primary stiffness Py/Dy in wind load or minor earthquake (Fig.2.d).



a. b c d

Fig.2 Characteristics of base isolation system

There are four kinds of system of base isolation and energy dissipation system for application : (1) Rubber pad (steel plates reinforced) as isolator. (2) Sliding pad as isolator combines with steel elements as energy dissipater . (3) Roller as isolator combines with steel elements as energy dissipater. (4) Friction layer or sand (or other material) sliding layer as isolator also energy dissipater.

One 8-stories concrete frame house building with base isolation used the rubber bearings is constructed in Shantou City in south China (Fig.3). Another 3 buildings with rubber bearings have been built and 8 buildings with rubber bearing will be built in south and north China. Most of isolation buildings built now have used the rubber bearings made by Shantou Industry Company of Vibration Isolation Product in China which are helped by UNIDO, MPRPA and EERC. Using these types of rubber bearings can assure the building safe in any strong earthquake, and it can reduce the cost of buildings about 5-20 % comparing with the traditional fixed base building. So, more and more buildings in China will use these types of rubber bearings (Zhou, 1990 b).

Four 4-7 stories brick buildings with sliding layer as isolator and steel elements as energy dissipater have been built in west China . Five low rise brick buildings with send sliding isolation have been built in north China (Zhou, *et al.*, 1994).

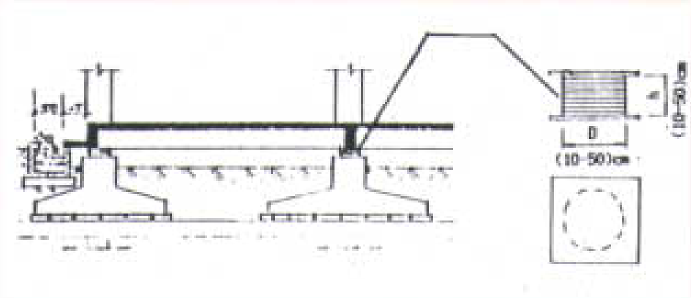


Fig.3 One 8 storied RC frame building with reinforced rubber pads

Testing and Analysis for Base Isolation System

Many tests have been finished and some sets of computation theory of seismic isolation system have been established in China now. The tests include two kinds of work:

Tests of isolators and energy dissipaters. Static tests of full scale elements, pseudo-static tests, low cycle fatigue failure tests. A series of pseudo tests were finished for rubber bearings, sliding layer, curved plates and friction layer.

Shaking table tests for large scale structural model. One 6 stories steel frame model is tested on the shaking table . The testing results are shown in Fig.4. The testing results show that: The acceleration responses on each stories of structure model are nearly the same. It means that the elements and joints of structure with base isolation nearly work within elastic range only. The acceleration response on structure with base isolation is only (1/3 - 1/10) response on structure fixed on shaking table. It means the base isolation is more effective to attenuate the structural response in earthquake than any other methods.

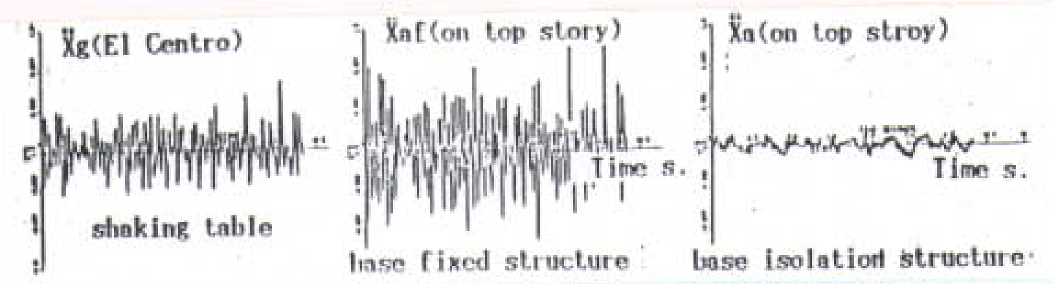


Fig.4 Testing results of shaking table with base isolation and base fixed model

The Computation Theory of Base Isolation System

From mathematics model, the basic differential equation of motion is given as:

$$M \ddot{X}a + Ce \dot{X}a + K Xa = Ce \dot{X}g + K Xg \qquad (1)$$

Where M is the structural mass. Ce is the equivalent viscous damping of isolating and energy dissipating system. K is the elastic stiffness of isolating and energy dissipating system. Xg $\dot{X}g$ $\ddot{X}g$ are the ground response of displacement, velocity and acceleration respectively in earthquake. Xa $\dot{X}a$ $\ddot{X}a$ are the structure response of displacement, velocity and acceleration respectively in earthquake.

Another basic differential equation of motion can also be written :

$$M \ddot{D}u + Ce \dot{D}u + K\, Du = - M \ddot{X}g \tag{2}$$

Where Du $\dot{D}u$ $\ddot{D}u$ are maximum relative displacement, velocity and acceleration respectively between structure and ground. Solve this equation with finding transfer function and get:

$$Du = \frac{\ddot{X}g}{W^2} \sqrt{\frac{(1-AR^2)\ (W/Wn)^2}{(W/Wn)^2-2}} \tag{3}$$

$$AR = \frac{\ddot{X}a}{\ddot{X}g} = \sqrt{\frac{1+4B^2}{4B^2+[1-(W/Wn)^2]^2}}\ \sqrt{\frac{W}{Wn}} \tag{4}$$

Define Wn and W as the NATURAL FREQUENCY of base isolation system and the ground motion. Define B = 2(1-1/U)/U as ENERGY DISSIPATION DAMPING RATIO, U = Du / Dy as DUCTILITY FACTOR. Where Du and Dy are the relative displacements at ultimate point and yield point. Where AR = $\ddot{X}a$ / $\ddot{X}g$ is called ACCELERATION ATTENUATION RATIO of system. The comparing the theoretical values Du and AR from Eq. (3) and (4) with the measured values approaches 1.0, it means that Eq. (3) and Eq. (4) give reasonable estimation. The author has also compiled a program EBIS-1 for design in engineering application.

ENERGY DISSIPATION SYSTEM

Design, Tests and Engineering Application

Two kinds of energy dissipation system to be used: (1)Energy Dissipation Components: such as Energy Dissipating Bracing or Energy Dissipating Shear Wall. (2) Energy Dissipating Damper : such as on bracing, shear wall, joints .

An industrial structure with energy dissipating bracing and another 28 storied high rise building with energy dissipating bracing has being built in Guangzhou, south China (Fig.5).

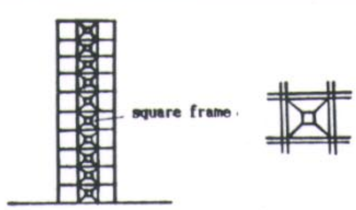


Fig.5 Energy dissipation bracing for high rise building

Fig.6 Tests for full scale model of friction bracing

In order to prove the behavior of this new bracing system, 5 sets of full scale models of this bracing have been tested (Fig.6). Base on the testing results, authors suggest some sets of computation programs for designing (Zhou, 1982).

Design and Calculation of Energy Dissipation System

For high rise building structure with energy dissipating bracing, the energy balance equation any instant of time during earthquake is:

$$Ein = Ep + Ek + Ep + Eb \tag{5}$$

Where Ein -- energy input to the structure. Ep -- potential energy in structural vibration. Ek-- kinetic energy in structural vibration. Ed--energy dissipated by viscous damping of structure. Eb--energy dissipated by bracing system (energy dissipater). Researches indicate that the energy dissipater can dissipate about 90% of the total energy input at the end of earthquake. So, some items whose effect are relatively small can be neglected in Eq.(5), then the energy dissipating design for earthquake resistance need to be satisfied with:

$$Ein < Eb \tag{6}$$

For calculating energy input Ein, the system can be considered as multi-degree of freedom system. The energy dissipated by bracing system Eb depends on the area enclosed by Load -Displacement loop curve(Zhou *et al.*, 1988)

TMD PASSIVE CONTROLLING STRUCTURE SYSTEM

The system is, on certain position (such as on roof) in structure, places an additional Filial Structure (possesses mass M, stiffness K and damping C) to change the dynamic characteristics of original structure. During the earthquake attack, the Filial Structure will move against the direction of original structural vibration and reduce the response of original structure. This Filial Structure is called TMD (Tuned Mass Damper). The system operates without any outside energy sources, so it is also called "Passive Controlling Structure System.

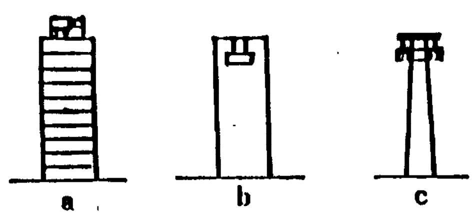


Fig.7 TMD passive control system

This system can reduce the response of structure very effectively. It is safe and very economic. It has been used in earthquake (or wind) resistant high-rise buildings, tower structure and some large span structures. One 192m height TV tower with TMD is designing in south China. There are three kinds of TMD are considered in China now (Zhou, 1992):

Supporting TMD (Fig.7.a). The Filial Structure is supported on the roof or other places in original structure. The Mass can move in bilateral directions.

Hanging TMD (Fig.7.b). The Filial Structure is hung at top of the original structure. The Mass can sway in any directions. In some cases, the water Tank on the top of the building may be designed as a Filial Structure hung at he top of building.

Impacting TMD (Fig.7.c). The Filial Structure is a Weight hung at the top place of structure. During earthquake, the hanging Weight will impact the original structure and reduce the response of structure.

ACTIVE AND HYBRID CONTROLLING STRUCTURE SYSTEM

The system is, on certain position in structure, places a additional Filial Structure which operates by computer control and immediately changes the dynamic characters of the structure to reduce the response of structure during earthquake. This system is controlled by outside energy sources , so is called "Active Controlling Structure System."

Three kinds of the system are studied in China (Zhou *et al.*,): one is, the Filial Structure possesses Mass, Stiffness and Damping, is called AMD (Active Mass Damper) Another is, the Filial Structure is a Bracing, is called Active Controlling Bracing. The third is, Hybrid active - passive system.

One Hybrid of Active Controlling Bracing with Passive Energy Dissipation System is designing for one 68 storied high rise building in south China. Some tests are doing for Active Controlling Structure System and Hybrid Controlling System in China now.

THE FUTURE DEVELOPING TENDENCY ABOUT SEISMIC CONTROL SYSTEM

The traditional earthquake resistant structure system and its design method have resulted in many problems in application. Since the Intensity of Earthquake is always uncertain, the ground motion and structural response are too complicated, and the requirement of structures with modern contents are more and more strict. The traditional system and its design method for earthquake resistant structures are not satisfied for usage. The new system of earthquake resistant structure will give a new way to resist earthquake for structures in seismic zone. The new system is more safe, effective, inexpensive and simple. Many engineers and scientists predict : " The coming decade will be a speed developing decade in Base Isolation, Energy Dissipation and Controlling Structure System in China and in the world !"

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